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Development of Advanced Multi-Modality Radiation Treatment Planning Software for Neutron Radiotherapy and Beyond

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Development of Advanced Multi-Modality Radiation Treatment Planning Software for Neutron Radiotherapy and Beyond

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Introduction

The Idaho National Engineering and Environmental Laboratory (INEEL) has long been active in development of advanced Monte-Carlo based computational dosimetry and treatment planning methods and software for advanced radiotherapy, with a particular focus on Neutron Capture Therapy (NCT) and, to a somewhat lesser extent, Fast-Neutron Therapy. The most recent INEEL software system of this type is known as SERA, Simulation Environment for Radiotherapy Applications[1]. As a logical next step in the development of modern radiotherapy planning tools to support the most advanced research, INEEL and Lawrence Livermore National Laboratory (LLNL), the developers of the PEREGRINE[2] computational engine for radiotherapy treatment planning applications, have recently launched a new project to collaborate in the development of a "next-generation" multi-modality treatment planning software system that will be useful for all modern forms of radiotherapy.

Background

In the 1980s, it became apparent that new computational methods were required to support large animal model preclinical NCT research, and anticipated human trials, for epithermal-neutron NCT in the United States. Computational approximations that work well for photon-electron therapy and, to some extent, fast-neutron therapy, are not appropriate for neutron capture therapy. Complete solutions of the transport equations, with an explicit treatment of particle scattering, are required. Standard Monte Carlo radiation transport codes used in other fields of nuclear science, for example MCNP[3], have often been used successfully for this purpose by various investigators. In addition specialized medical image based geometric reconstruction and radiation dose visualization interfaces have been introduced for use with an especially tailored version of MCNP to produce a practical treatment planning system for BNCT[4,5].

However, MCNP and other general-purpose transport codes are designed for very broad applications. They can tend to be somewhat slow in execution relative to expectations for treatment planning in clinical oncology practice (a few minutes per field, maximum), and there are limitations in the geometric detail that can be modeled. Hence, a project was initiated at the INEEL in 1988 to develop a special-purpose medical image based Monte Carlo system optimized specifically for radiotherapy, with epithermal-neutron boron neutron capture therapy (BNCT) as the first anticipated application. This initial effort, conducted in collaboration with the University of Utah Department of Computer Science, resulted in the BNCT_edit system[6].

In 1994 BNCT_edit was replaced by a much-improved system, BNCT_rtpe (BNCT Radiation Treatment Planning Environment)[7]. BNCT_rtpe was developed by the INEEL in collaboration with the Montana State University (MSU) Department of Computer Science. It was based on experience gained with the BNCT_edit development effort in that it featured a sophisticated Non-Uniform Rational B-Spline (NURBS) approach to image modality independent reconstruction of patient geometry from medical images[8]. Although BNCT_rtpe proved to be a useful and relatively efficient clinical research tool there still was a need to reduce the computation time further. Accordingly, INEEL and MSU undertook some studies in the late 1990s that were focused on achieving a significant breakthrough in execution speed via a total reformulation of the mathematical algorithms. The result of this developmental effort led to the introduction of the completely new SERA[1] treatment planning software in 1998.

The SERA treatment planning system incorporates an integrated method for reconstructing patient geometry from medical images and for subsequently tracking particles through this geometry during a Monte Carlo radiation transport simulation. The method is based on a pixel-by pixel uniform volume element ("univel") reconstruction of the patient geometry[9]. As with the B-Spline method, construction of the patient geometry is independent of the medical image modality and field of view. Fast scan-line rasterization methods, implemented largely with integer arithmetic, are then used to allow rapid particle tracking through the univel geometry. The geometric fidelity of the NURBS reconstruction method is retained, but certain numerical difficulties are eliminated. Furthermore, the computed fluxes and doses have the same statistical accuracy as with a NURBS model, but the execution time for the transport computations is reduced by a factor of between five and ten. This speedup factor holds even though the new univel model may consist of several million elements. Single-CPU execution times for SERA, with current desktop scientific computing hardware (e.g. Pentium™ systems running under Linux), are in the range of a few minutes per field for neutron applications.

The PEREGRINE dose calculation system[2] is primarily designed to provide Monte Carlo transport calculations fast enough for day-to-day external-beam photon-electron radiation therapy planning, although computations for other types of radiotherapy using specialized versions of PEREGRINE are also possible. PEREGRINE simulates radiation therapy starting with a set of representative particles randomly sampled from energy, angle, and position distributions determined from offline simulations of the treatment-independent portion of the radiation source. It tracks each photon, electron, and positron through the treatment-dependent beam delivery system and then through the patient using random numbers, microscopic particle-interaction probabilities, and other standard Monte Carlo transport methods. As each particle interacts, it sets in motion other particles that are also tracked.

Treatment-specific beam modifiers such as collimators, apertures, blocks, multileaf collimators, and wedges are modeled explicitly during each PEREGRINE calculation. Each component is described in terms of its physical dimensions, material composition, and density. The patient is described as a Cartesian map of material electron density determined from the patient's CT scan. Each CT pixel defines the electron density of a corresponding transport mesh voxel. Material composition is determined from user-defined CT threshold values. Density is determined from a user-defined piecewise-linear function that describes the CT-number-to-density conversion. PEREGRINE records the dose deposited by each particle in a uniform Cartesian dose collection mesh that consists of packed dose-collection spheres.

Future Directions

With SERA and PEREGRINE at mature stages in their respective life cycles, INEEL, MSU and LLNL have now combined forces to launch a new project to collaborate in the creation of a multi-modality treatment planning software system that will draw on the combined experience of the three institutions in their respective areas of interest. It will feature several important new functionalities made possible by recent advances in computational hardware, software, and operating system technology. The objective will be to create an integrated software system that is useful for all modern forms of radiotherapy. The new system will carry the name MINERVA (Modality-Inclusive Environment for Radiotherapeutic Variable Analysis).

Several state of the art features will be incorporated into the new system. With the advent of the Java™ internet-based programming language, it is now possible to produce extremely sophisticated software and graphic user interfaces with much greater portability among various computer hardware platforms. In addition, the focus will be on the development of a system that can be easily tailored to any radiotherapy modality (and to include multiple computational methodology options for a given therapeutic modality) via an open "plug-in" based interface environment. The first version of MINERVA will include capabilities for external beam photon, electron and fast-neutron radiotherapy, neutron capture therapy, and molecular targeted radionuclide therapy. Other anticipated additions include new computational modules optimized for external-beam proton therapy, as well as for brachytherapy. Alternate computational methods based on existing transport software such as MCNP could also be incorporated by providing an appropriate interface. The new system will employ multi-modality image sets for treatment plan development and it will implement a universal data base for patient information file storage (with interfaces to accommodate standard clinical data communication protocols and formats such as RTOG, DICOM-RT, etc.).

In anticipation of this longer-term joint developmental program, INEEL and LLNL have completed some initial computational feasibility studies for a combined software system. These studies employed an internet-based *ad hoc* coupling of the functionalities in the SERA and PEREGRINE code systems as they currently stand. These initial studies have successfully demonstrated that there should be no fundamental difficulties with the development of the key computational and data interfacing functions that will be required in the new system.

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